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A METHOD FOR THE ANALYSIS OF INTERRELATIONSHIPS BETWEEN MUTUALLY CONNECTED EVENTS

An attempt to improve on the traditional cross-impact method

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1 — Introduction

It is not uncommon in planning and forecasting that the joint probability factors (events) related to one another must be determined or that the impacts of several events upon one another must be estimated. In working out national economic plans, for instance, economists must consider the fact that improvement in economic management affects the efficiency at which factors of production are utilized, technological progress, foreign trade and, in general, the economic growth and situation of the country. In its turn, a better economic situation may create opportunities for introducing further modifications in the economic management system to suit modified conditions.

Thus the events referred to form a loop of positive interactions.

These — and similar — interactions can be described with qualitative factors and consequently cannot be quantified in traditional ways, so the chain reaction elicited by a given event (economic measure) is rather difficult to follow.

What is generally referred to as the cross-impact method has been developed to analyse interrelationships between factors that cannot or can hardly be quantified. The best known representatives of this method are T. J. Gordon, S. Enzer and O. Helmer, whose aim — among other things — has been to eliminate a shortcoming of the Delphi method, namely that forecasts on the probability of events are given separately, thus interrelationships between these events are disregarded. However, the method presented by the authors mentioned above fails to answer certain questions related to the theoretical interpretation of interrelationships between events; such is, at least, the opinion of the authors of the present paper. Therefore an attempt has been made here to present a new method — referred to as the *method for the analysis of interrelationships between mutually connected events* — to keep it distinct from other cross-impact methods, which is based on the principle laid down by the American authors and is adapted to the socialist planning system. This method makes it possible to estimate the probability of occurence of interrelated events, investigate the chain of effects of certain

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measures or events and explore and eliminate contradictions between forecasts for mutually related events.

To test the method, the authors applied it in examining the cross-impacts of factors determining economic growth in Hungary and in presenting a long term forecast for economic growth. The results presented should be interpreted *as illustrations to the practical application of the method rather than meaningful economic figures,* even though several of them correspond with various opinions on the subject derived from entirely different sources. It is a shortcoming of the method described here that it fails to treat the subject on the plane of general probability calculus, and the authors had to be content to testify the method solely on the basis of empirical data. As all computations in the method have yielded meaningful results, it is presumed that this kind of analysis can be used for solving actual problems.

2 — The computation algorithm

Similarly to the cross-impact analysis, the method is based on the assumption that the occurrence of one event of a system of interrelated events may modify the probability of the other events. The method is thus an algorithm that defines the degree in which the occurrence or non-occurrence of certain happenings may modify the initial probabilities of events as forecasted by experts.

2.1 – Events and initial probability

The first step in applying the method is to define a *set of events* that bear relationships towards one another and which are related to the object investigated. After this follows the determination of initial probabilities.

Initial probability (p_j or p_i) is the probability of occurrence of an event or a trend forecasted by experts who, in so doing, do not consider systematically the effects of the other individual events; rather, they try to assess the overall impact these events may exert, i. e., they seek to consider a «scenery» of events with the aggregate of their specific effects.

Producing forecasts for the probability of an event of single occurrence is a delicate matter that poses a number of questions. In the case of events that will or will not take place on a single occasion in the future, the traditional interpretation of probability must be dispensed with. It is true, however, that the occurrence of an event may have a smaller or greater probability as the case may be. And although this probability cannot be quantified accurately, certain qualitative categories with probability ranges related to them may be set up.

The following categories and ranges of probability are used in the present method:

Probability	Interpretation
0,0 — 0,2	Event of single occurrence, with very low probability.
0,21 — 0,4	Event of single occurrence, with relatively low probability.
0,41 — 0,6	Event of single occurrence, with about «fifty-fifty» probability.
0,61 — 0,8	Event of single occurrence, with relatively high probability.
0,81 — 1,0	Event of single occurrence, with very high probability.

The initial probabilities of events of single occurrence are given as the expected value of a mathematical function fitted to relative expert estimations. In case the number of events is insufficient for fitting a function (e. g. the conditions of the χ^2-test are not given), the arithmetic mean of probabilities has to be used, or it is also reasonable to take the median as the initial probability of events or trends.

2.2 – Maximum and minimum probabilities

The initial probabilities in a set of interrelated events may be modified through interaction. The modified values must, of course, remain in the interval [0, 1]; nevertheless, the actual interval to be considered is narrower than the theoretical one, since certain events may also be influenced by events not belonging to the given set.

The probability of the occurrence of an event is considered *maximum* (p_{max}) if all other events related to this event have or have not occurred in a way to enhance its probability, whereas the probability of the occurrence of an event is *minimum* (p_{min}) in the opposite case.

The maximum and minimum values of probability can be calculated from expert estimations in a way similar to that used for the initial probabilities.

2.3 – Cross-impact matrix

The *cross-impact matrix* contains expert estimations referring to the *strength, direction* and *quality* (positive or negative) of interrelationships between events. To assess what type of linkage exists between each pair of events, experts are invited to give their opinions. They are required to decide which of two events is the cause and which the result, and what is the strength and mode of linkage.

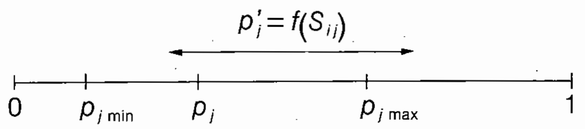
The present study classifies linkages according to strength using numerals in the following way:

0, if event$_i$ and event$_j$ are not or insignificantly related;
1, if event$_i$ and event$_j$ are moderately related;
2, if event$_i$ and event$_j$ are medium-related;
3, if event$_i$ and event$_j$ are closely related.

The quality of the interrelationships is indicated by minus and plus signs. The direction of interrelationships is shown by the structure of the table: the events appearing on the left-hand side influence the events appearing at the top.

In the practical application of the method, every expert invited to take part compiled a cross-impact matrix, in which the absolute value of an s_{ij} element in column$_j$ of row$_i$ indicated the closeness of relationship and the sign preceding the figure indicated the quality of relationship. (If it is positive, event$_i$ enhanced the probability of event$_j$, and in case it is negative, event$_i$ reduced the probability of event$_j$.)

The next step was to summarize the elements of the tables given by experts. This new table which contains arithmetical sums of the individual estimations became the basis for further research. (Elements of the new table are indicated by S_{ij}.) The authors assumed that modifications in the probability of an event between the minimum and maximum values are proportionate to the S_{ij} values found in the matrix table, i. e., so-called changed probability values are a linear function of S_{ij}.



As has been mentioned, the probability of an event is maximum if all other developments work in favour of the occurrence of the event, i. e., if all events that have a positive impact on the event occur, whereas those having a negative impact do not. The authors postulated that the effects produced by occurrence and non-occurrence are of a symmetrical nature, i. e., if the occurrence of event$_i$ has $+S_{ij}$ impact on event$_j$, then the non-occurrence of event$_i$ has a $-S_{ij}$ impact.

In order to simplify calculations, the elements of the cross-impact table were normalized so that the vertical sum of the absolute values of S_{ij} elements in each column should be 1. The *normalized value* of an element is thus:

$$z_{ij} = \frac{S_{ij}}{\sum_{i=1}^{n} |S_{ij}|} \qquad j = 1, 2, \ldots, n$$

where n is the number of events considered. According to the definition, z_{ij} is in the range -1 to $+1$.

Hence it is possible to draw up an initial matrix which helps to consider the chain reactions of events (see appendix 2). It should be noted — as can be seen also in appendix 1 — that the possible outcomes of trends were treated as three events, which are mutually exclusive.

2.4 – Hierarchy of the elements of the set of events

Events can be often arranged into a hierarchical order according to interrelationships. This is particulary valid in respect to sets of events connected with the growth of development processes. The arrangement is a different procedure with each set of events and requires several criteria to be considered.

The possible way for the determination of hierarchy is e. g. as follows: where the top place is occupied by the event that affects the greatest number of other events, and other events are placed in accordance with number of interrelationships they maintain. Another mode of establishing hierarchy is to add up the absolute values of the elements (S_{ij}) in each row and to place the event belonging to the greatest sum thus obtained at the top of the hierarchy.

Hierarchy of events is of great importance in the calculation of so-called changed probabilities: if the occurrence or non-occurrence of events is considered in the order of hierarchy — as is to be seen later —, the calculation will be simplified considerably. Appendix 2 displays events in the order of hierarchy as established by the authors. It is to be noted that the hierarchical order of a set of events is not necessarily exclusive; the graph representing the set may contain loops, which makes, in certain cases, hierarchy a matter of consent.

2.5 – Runs and cycles

After presenting the initial stages in the method, the paper will proceed to elaborate a detailed algorithm. In the case of existing hierarchy, the first thing is to compare the initial probability of the event on top of the hierarchy with a number chosen at random in the interval 0 to 1. If the initial probability is equal to or higher than the number, the event is to be regarded as having occurred, and if it is smaller, not occurred, and consequently the initial probability of the event to come next in the hierarchy is to be changed according to the normalized cross-impact table.

Change is effected on the basis of the following formulae:

$$p'_j = p_j + (p_{j\,\max} - p_j) \sum_{i=1}^{h} z_{ij} \qquad \text{if } \sum_{i=1}^{h} z_{ij} \geqq 0$$

$$p'_j = p_j + (p_j - p_{j\,\min}) \sum_{i=1}^{h} z_{ij} \qquad \text{if } \sum_{i=1}^{h} z_{ij} < 0$$

where:

p'_j is the *changed probability* of event$_j$;
p_j is the initial probability of event$_j$;
$p_{j\max}$ and $p_{j\min}$ are the maximum and minimum probabilities of event$_j$;
h is the serial number of the element$_{j-1}$ in the hierarchy ($h = 1, 2, \ldots, n-1$).

In the present case (see appendix 3) the event at the top of the hierarchy (event 1) had an initial probability of 0,5 and the random number was 0,12. As the initial probability was greater than the random number, the event was considered to have occurred. Event 1 thus has an impact of +0,44 ($z_{12} = +0{,}44$, from appendix 2) on event 2 in the hierarchy. In consequence, the probability of event 2 is changed:

$$p'_2 = p_2 + (p_{2\max} - p_2)\sum_{i=1}^{1} z_{i2} = 0{,}5 + (0{,}6 - 0{,}5)\cdot 0{,}44 = 0{,}54$$

The changed probability of event 2 (0,54) being found smaller than its random number (0,84), event 2 is to be regarded as not having occurred. So far, event 1 has occurred, and event 2 has not occurred. Thus the probability of event 3 in the hierarchy is calculated:

$$p'_3 = p_3 + (p_{3\max} - p_3)\sum_{i=1}^{2} z_{i3} = 0{,}6 + (0{,}9 - 0{,}6)\cdot(0{,}33 - 0{,}2) = 0{,}64$$

(As event 2 did not occur, the value $z_{23} = 0{,}2$ in the cross-impact matrix is considered negative.)

The random number related to event 3 (0,82) is again higher than the changed probability of the event (0,64), so event 3 did not occur. Hence, the changed probability of event 4 is:

$$p'_4 = p_4 + (p_{4\max} - p_4)\sum_{i=1}^{3} z_{i4} = 0{,}6 + (0{,}8 - 0{,}6)\cdot(0{,}5 - 0{,}5) = 0{,}6$$

The calculation must proceed until event n is reached. In the case of trends, the changed probabilities for the three outcomes of the trends [8, *a*), 8, *b*), 8, *c*), 9, *a*), 9, *b*), 9, *c*)] have to be calculated at the same time. From the three outcomes that has to be attributed occurred where the ratio of changed probability and random number is the greatest.

When computations for each element have been completed, *phase A of one run* is obtained. Now changed probabilities of all events must again be calculated on the basis of the *final* table produced by phase *A*, taking into account all the events — not only the preceding event in the hierarchy. In this case, the value of h is $n - 1$ for each event. This is called *phase B* of the run. Phase *B* is needed to consider the effect of possible loops in the hierarchy, i. e., a given event is affected by another standing in a lower place in the hierarchy. If the changed probabilities bear the same relationships to their relative random numbers after phase *B* as they did before, then the run is over, since feedbacks have not been found to modify previously determined occurrences and non-occurrences in the given set of events.

For exemple, from the data in appendix 3 (in phase *A* — 1) we know that events 1, 5, 6, 8, *c*), and 9, *a*), have occurred and the others haven't occurred. So we get (from the data in appendix 2 and 3):

$$\sum_{i=Z}^{13} {}^{i}z_{i1} = -0{,}2+0-0{,}23+0{,}18+0+0+0+0+0{,}14+ +0+0-0{,}25 = -0{,}36$$

$$p'_1 = 0{,}5+(0{,}5-0{,}2)\,(-0{,}36) = 0{,}39$$

The random number related to event 1 (0,12) is smaller than the changed probability of the event 1 (0,39), so event 1 has occurred in the phase *B* as in the phase *A*.

If, as phase *B*, which considers the effect of the totality of the set of events, the relationship between a probability value and its random number is found to have been inverted as compared to that after phase *A*, then the probabilities of all events related to this one must be calculated again, i. e., the chain reaction of inversions must be determined. This is done in phases B_1, B_2, etc. When phase B_i yields the same results as B_{i-1} for each of the events, the run is completed.

It is also possible for the probability of an event to alternate its relationship to its relative random number by being higher and lower in regular succession. In this case, the probability of occurrence of the event is said to be between the two values, and the run oscillates.

The runs must be repeated with different sets of random numbers until the relative frequency of occurrence of each event shows a marked tendency towards a limit, the so-called *modified probability* of the event. The calculation of modified probability theoretically requires an infinite number of runs, in practice, however, it is sufficient to have so many runs that the range (amplitude) in which the relative frequency of each event moves is less than one fourth of the width of the probability range in about ten runs in succession. (The amplitude in the present case is 0,2 : 4 = 0,05.)

A series of runs was called as the cycle.

2.6 – Sensitivity analysis

Certain events in the set may be affected by events not belonging to the given set which is bound to modify their initial values of probability. Calculations based on these modified initial values, or *sensitivity analysis,* may help to find out how external events may affect the rest of the elements in the set. Computation is similar to the method described above. Naturally, the initial probabilities of the elements involved in the sensitivity analysis differ from those in the primary calculations.

3 — Results of experimental calculations

We have summarized the numerical results of the experimental calculations in the appendix 5. Analysing these data it can be seen that the experts — forecasting the initial probabilities — were almost unanimous in predicting increasing problems in acquiring raw materials and fuels and increasing pollution, and also in finding little hope for substantial increase in the national income growth rate and in the efficiency of fixed assets. Opinions differed as to adopting new methods in the system of economic control and management, more efficient use of the basic materials and the reality of large-scale investments for environmental protection.

The given set of events had very little effect on efficiency of using basic materials, the maximum and minimum probabilities of which are hardly different from the initial value. The greatest effect was found in the case of efficiency of fixed assets and national income growth rate, whose probabilities range in wide intervals.

The cross-impact matrix indicates that adopting new methods in the system of economic control and management to suit the requeriments of our times would bear on almost all other events significantly. On the other hand, the adaptations of new management methods were urged by the increase in qualifications. Up-to-date management methods might counterbalance such negative trends as worsening efficiency of fixed assets, slackening national income growth rate and increasing problems in acquiring raw materials. In fact, these events would force economists to adopt new management methods, and in this case a modernization could only be expected by the end of the period investigated. (This would make it necessary to split the event into the occurring at the beginning and another at the end of the period.)

As it is seen from the cross-impact matrix, the increasing efficiency of using basic materials would promote further efficiency of fixed assets, would ease problems in acquiring raw materials and stimulate economic growth. On the other hand, up-to-date economic management and increasing technological progress would improve efficiency of using on materials. A marked increase in qualifications would step up technological progress and improve management methods, but it also depends on both technological progress and efficient management. The prevention of environmental pollution could only be achieved through large-scale investment, which is dependent upon a larg number of rather vague factors.

As has been seen, certain events form a positive feedback loop, i. e., an event has a positive impact on several others, which, in their turn, contribute to the increasing of the probability of occurrence of the initial event, either directly or involving other events. If these relationships are represented in a graph, they will appear as interconnected closed cycles. The graph obtained by the method described is shown in appendix 4. (The graph only indicates impacts of greater values than 0,15.)

The synthetic results show that modified probabilities are usually different from initial ones. The probability of the new management methods has grown from 0,5 to 0,56, owing to cross-impacts, and there appears an increase in the probability of a marked increase in qualifications. The probability of the increasing problems in acquiring raw materials and growth in pollution has been slightly reduced. The differences, however, are not substantial: they are no greater than half of the range of probability in question (5 ranges were set up, each 0,2 «in width», and the maximum shift in probability was 0,08.) This means that the *method for the analysis of interrelationships between mutually connected events has confirmed the independently forecasted probabilities, i. e., there is no substantial inconsistency between forecasts for individual events and forecasts for cross-impacts.*

When the results of each of the runs are known, it is also possible to determine the joint probability of two (or more) interrelated events. Events 2, 3 and 4 in the present analysis have positive interrelationships between them. If these events were independent of one another, then the joint probability of their occurrence would be the product of their initial probabilities: $0{,}5 \cdot 0{,}6 \cdot 0{,}6 = 0{,}18$. In contrast, it must be observed that all three events occured simultaneously 18 times out of 50 runs, which puts their relative frequency at 0,36, which in turn means that the joint probability of the simultaneous occurrence of all three events is almost double of the value that was obtained when mutual dependence was disregarded.

The *sensitivity analysis* showed the effects a modernization of the system of economic control and management and marked increase in qualifications would have on the elements of the set (the initial probabilities of event 1 and 4 were 1). The most significant change was that the probability of increasing in the rate of technological progress was raised from 0,6 to 0,8 and the probability of worsening efficiency of fixed assets and decreasing rate of national income growth decreased. If, however, it is presumed that economic management is not modernized and there is no marked increase in qualifications (initial probabilities of events 1 and 4 were 0), then the probability of decelerating technological progress and decreasing national income growth rate increased.

The calculations have resulted in figures that easily lend themselves to practical interpretation and throw light on hidden relationships otherwise not easily detected.

4 — Scope of the method for the analysis of interrelationships between mutually connected events

As other cross-impact methods, the present one is used for analysing and forecasting interrelationships between events that can be described numerically with great difficulty, if at all. The present method helps to make decisions by offering consistent forecasts for a set of interrelated events.

The possible fields of application of the method are as follows:

- Quantifyng the effects of decisions and measures not hitherto qualified, e. g., determination of certain parameters influenced by other events in the case of economic planning; analysis of decrees or events in mutual relationship and future effects in politics and society;
- Analysis of the chain reaction of single events or measures;
- Testing consistency within a group of forecasts related to the same events.

Besides the above-mentioned, the present method can be regarded as having the greatest advantage: that it helps to avoid excessive subjectivity in estimating probabilities of occurrence of events.

Appendix 1

Events

1 — Adopting new methods in the system of economic control and management.
2 — A more efficient use of the basic materials.
3 — Considerable increase in the rate of technological progress.
4 — Marked increase in qualifications (measured by the level of education of the active population).
5 — Increasing problems in acquiring raw materials and fuels.
6 — Large-scale investments for environmental protection.
7 — Increasing pollution of the environment.
8, *a*) Growing efficiency of fixed assets.
8, *b*) No change in efficiency of fixed assets.
8, c) Diminishing efficiency of fixed assets.
9, *a*) Increase in national income growth rate (ca. 1,0 %).
9, *b*) No change in national income growth rate.
9, c) Decrease in national income growth rate (ca. 1,0 %).

Basic data

Normalized cross-impact matrix (1)

Events	$p_{min.}$	p_j	$p_{max.}$	1	2	3	4	5	6	7	8, *a*)	8, *b*)	8, *c*)	9, *a*)	9, *b*)	9, *c*)
1	0,2	0,5	0,8	-	0,44	0,33	0,50	-	0,15	— 0,16	0,28	-	— 0,20	0,10	-	— 0,10
2	0,4	0,5	0,6	0,20	-	0,20	-	— 1,0	0,08	-	0,17	-	— 0,17	0,08	0,37	— 0,08
3	0,4	0,6	0,9	-	0,56	-	0,50	-	0,09	-	0,20	-	— 0,14	0,14	-	— 0,14
4	0,5	0,6	0,8	0,23	-	0,32	-	-	-	-	0,10	-	— 0,10	0,10	-	— 0,07
5	0,6	0,8	0,9	0,18	-	-	-	-	-	0,14	— 0,10	-	0,12	— 0,10	— 0,23	0,15
6	0,3	0,5	0,8	-	-	-	-	-	-	— 0,56	— 0,15	-	0,21	— 0,10	-	0,05
7	0,6	0,8	0,9	-	-	-	-	-	0,24	-	-	-	0,06	-	-	0,05
8, *a*)	0,0	0,2	0,5	-	-	-	-	-	0,08	-	-	-	-	0,17	-	— 0,16
8, *b*)	0,3	0,3	0,3	-	-	-	-	-	-	-	-	-	-	— 0,04	-	-
8, *c*)	0,0	0,5	0,8	0,14	-	— 0,06	-	-	-	-	-	-	-	— 0,17	— 0,40	0,20
9, *a*)	0,0	0,2	0,8	-	-	0,09	-	-	0,25	0,14	-	-	-	-	-	-
9, *b*)	0,2	0,4	0,8	-	-	-	-	-	-	-	-	-	-	-	-	-
9, *c*)	0,1	0,4	0,8	0,25	-	-	-	-	— 0,11	-	-	-	-	-	-	-

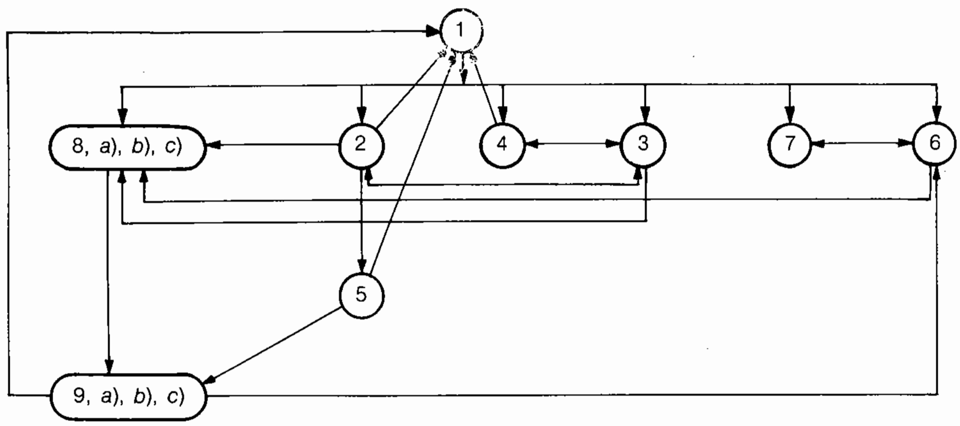
(1) Values of $z_{ij'}$ if event$_i$ happens.

Results of first run

Events	Randon - Nembers	P_j	Phase A P_j	Phase A (a)	Phase B P_j	Phase B (a)	1	2	3	4	5	6	7	8, a)	8, b)	8, c)	9, a)	9, b)	9, c)
1	0,12	0,5	-	+	0,39	+	-	0,44	0,33	0,50	-	0,15	— 0,16	0,28	-	— 0,20	0,10	-	— 0,10
2	0,84	0,5	0,54	—	0,49	—	— 0,20	-	0,20	-	1,0	— 0,08	-	— 0,17	-	0,17	— 0,08	— 0,37	0,08
3	0,82	0,6	0,64	—	0,57	—	-	— 0,56	-	— 0,50	-	— 0,09	-	— 0,20	-	0,14	— 0,14	-	0,14
4	0,90	0,6	0,60	—	0,60	—	— 0,23	-	— 0,32	-	-	-	-	— 0,10	-	0,10	— 0,10	-	0,07
5	0,22	0,8	0,90	+	0,90	+	0,18	-	-	-	-	-	0,14	— 0,10	-	0,12	— 0,10	— 0,23	0,15
6	0,18	0,5	0,50	+	0,50	+	-	-	-	-	-	-	— 0,56	— 0,15	-	0,21	— 0,10	-	0,05
7	0,86	0,8	0,68	—	0,71	—	-	-	-	-	-	— 0,24	-	-	-	— 0,06	-	-	— 0,05
8, *a*)	0,30	0,2	0,11	—	0,11	—	-	-	-	-	-	— 0,08	-	-	-	-	— 0,17	-	0,16
8, *b*)	0,24	0,3	0,30	—	0,30	—	-	-	-	-	-	-	-	-	-	-	0,04	-	-
8, *c*)	0,17	0,5	0,66	+	0,66	+	0,14	-	— 0,06	-	-	-	-	-	-	-	— 0,17	— 0,40	0,20
9, *a*)	0,03	0,2	0,06	+	0,06	+	-	-	0,09	-	-	0,25	0,14	-	-	-	-	-	-
9, *b*)	0,46	0,4	0,20	—	0,20	—	-	-	-	-	-	-	-	-	-	-	-	-	-
9, *c*)	0,51	0,4	0,68	—	0,68	—	— 0,25	-	-	-	-	0,11	-	-	-	-	-	-	-

(a) + : The event was considered to have occurec;
— ; The event was considered not to have occurec.

Appendix 4



Graph-representation on interrelationships between mutually connected events

Appendix 5

Synthetic results

Events	p_{min}	Initial probability	p_{max}	Modified probability	Sensitivity analysis	
					$p_1 = 1,0$ $p_4 = 1,0$	$p_1 = 0,0$ $p_4 = 0,0$
1	0,2	0,5	0,8	0,56	1,0	0,0
2	0,4	0,5	0,6	0,52	0,60	0,46
3	0,4	0,6	0,9	0,64	0,80	0,48
4	0,5	0,6	0,8	0,68	1,0	0,0
5	0,6	0,8	0,9	0,74	0,74	0,74
6	0,3	0,5	0,8	0,55	0,56	0,47
7	0,6	0,8	0,9	0,74	0,72	0,75
8, *a*)	0,0	0,2	0,5	0,22	0,36	0,08
8, *b*)	0,3	0,3	0,3	0,29	0,30	0,20
8, *c*)	0,0	0,5	0,8	0,49	0,34	0,72
9, *a*)	0,0	0,2	0,8	0,22	0,32	0,10
9, *b*)	0,2	0,4	0,8	0,34	0,36	0,38
9, *c*)	0,1	0,4	0,8	0,44	0,32	0,52

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